Pergamon

Deep-Sea Research I, Vol. 42, No. 11/12, pp. 2113–2126, 1995

0967–0637/95 $9.50+0.00

0967–0637(95)00078–X

MKIIIB-CTD: improving its system output

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(*Received* 8 *April* 1994; *in revised form* 25 *November* 1994; *accepted* 15 *December* 1994)

Abstract—In the Neil Brown Instruments' MKIIIB-CTD (conductivity–temperature–depth profiler), the system's digital outputs for the three basic measurements of temperature, conductivity and pressure typically show some small amplitude deviations from smooth calibrations which should be corrected for to achieve high accuracies, as required, e.g. within the Hydrographic Program (WHP) of the current World Ocean Circulation Experiment (WOCE). These deviations show up as (i) a strong nonlinearity or even discontinuity of several mK close to 0°C in temperature output leading to too high subzero temperatures; (ii) a jump of order 0.002 mS cm^{-1} in conductivity output when passing the half-range value 32.768 mS cm^{-1}, which causes jumps in the relation of potential temperature and salinity; and (iii) errors in pressure measurements of up to 4 dbar due to mechanical hysteresis and both static and dynamic responses to temperature changes. The existence of these effects is demonstrated, and methods to reduce the associated errors are suggested.

1. INTRODUCTION

Since its invention more than 20 years ago, the MKIIIB-CTD (see Fofonoff *et al.*, 1974; Brown and Morrison, 1978) proved an accurate and reliable and, therefore, widely used tool to continuously measure the three physical parameters of sea water necessary to determine its state: pressure, temperature and electrical conductivity. Although new technologies are now available, it is obvious that the MKIIIB will, at least for a few more years, serve in international measuring campaigns like the ongoing WOCE (World Ocean Circulation Experiment) Hydrographic Program (WHP).

Required accuracies for hydrographic measurements in the WHP (see WMO, 1988) namely 2 mK, 0.05% and 0.002 for temperature, pressure and salinity, respectively, challenge measurement and calibration techniques, and it was only recently that careful laboratory calibrations and investigations of *in situ* data have revealed some typical features of MKIIIB measurements which appear as small deviations from low order, smooth sensor calibrations and which must be corrected for to meet the WHP requirements. We will demonstrate the existence of such small deviations typical for the MKIIIB and discuss how to treat them. However, we will not go further in data processing procedures, which are beyond the scope of this contribution. This paper summarizes a

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more detailed description (Müller *et al.*, 1994) reported to the WOCE Hydrographic Program Office.

We start with a discussion of the shape of the temperature sensor's calibration, which typically shows a strong nonlinearity, in some instruments even a discontinuity of several mK in the calibration close to 0°C. With present instrumentation, this feature can be detected only in careful laboratory calibration and only if calibration points at temperatures <0°C are obtained. By a modification in the hardware, this discontinuity can be shifted to −3°C, outside the oceanic range.

Conductivity output may also have a discontinuity. It is of order 0.002 mS cm^{-1} and occurs at half-range sensor output at 32.768 mS cm^{-1}. It was first observed in profiles from the deep northeast Atlantic Ocean as a discontinuity in the relationship between potential temperature and salinity, and then confirmed on other instruments and in different water masses.

In the MKIIIB, a strain gauge sensor is used to measure pressure. It is well known that this type of sensor has a mechanical hysteresis and that it also responds to temperature changes, both statically and dynamically. Effects of hysteresis and static temperature response may lead to deviations from the basic loading calibration at a fixed temperature by several dbar. The dynamic pressure response to sudden temperature changes may be of order 0.3 dbar K^{-1} and larger, and thus may be relevant in strong temperature gradients, such as those that occur in the near surface thermoclines of the tropics. These features, too, can be measured only in laboratory experiments. We discuss methods of compensating for these responses.

2. TEMPERATURE RESPONSE CLOSE TO 0°C

In the MKIIIB, the precision temperature is measured with a platinum resistance Pt100 at a resolution of 0.5 mK in the oceanic range, i.e. roughly between −2 and 29°C. To avoid mismatches in time constants of the (slow) platinum resistance and the (fast) conductivity cell, the original MKIIIB combines the signal of the Pt100 with the high-pass filtered signal of a fast thermistor response, and it is this combined signal which is displayed on deck units and output to computer interfaces. We deal here only with slow temperature changes for which the combined output essentially is the same as for the Pt100 alone and which, therefore, can be used in the discussion below. Also, disabling the fast response sensor will not affect the results.

In 1990, the International Temperature Scale (ITS90) was invented. It replaces the older International Practical Temperature Scale of 1968, IPTS68, on which all MKIIIB-CTD temperature sensors are calibrated on delivery from the manufacturer. A simple linear conversion from the IPTS68 to the ITS90 for the oceanic range has been proposed by Saunders (1991) and is recommended for application by the Joint Panel on Oceanographic Tables and Standards, JPOTS. The relation is:

$$T_{90} = T_{68}/1.00024. \tag{1}$$

To consistently use the ITS90, in the following all temperature corrections are referred to the new scale. Note that this conversion shifts correction curves to lower values at high temperatures but that, because it is linear, it does not affect the discussion below.

Usually, the platinum sensor is provided by the manufacturer together with an electronic card which carries the sensor's basic linear calibration on the IPTS68. This

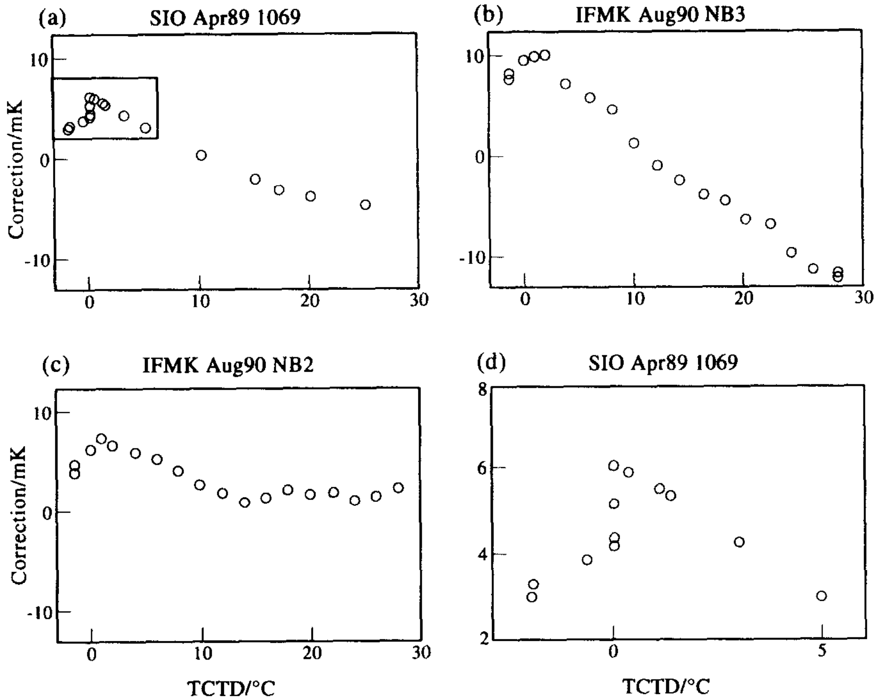

Fig. 1. Corrections to be applied to basic temperature calibrations of MKIIIB CTDs to meet the ITS90 temperature scale: (a) S/N 1069 of the Alfred Wegener Institut, Bremerhaven, was calibrated at the Scripps Institution of Oceanography (SIO) in April 1989; (b) NB3 and (c) NB2 were calibrated at the Institut für Meereskunde, Kiel. Note the strong nonlinear deviations of order 2 mK from low order regressions close to 0°C, which for S/N 1069 is blown up in (d).

internal calibration is such that the instrument has zero voltage output at 0°C and it seems that at zero voltage output the analog–digital conversion gives rise to problems in all instruments tested.

In Fig. 1 we display the corrections needed on three different instruments, to be added to the temperature output T_{CTD}, to meet the ITS90. The MKIIIB-CTD S/N 1069 (Fig. 1a) is owned by the Alfred Wegener Institut, Bremerhaven, Germany, and was calibrated at the Scripps Institution of Oceanography (SIO) in April 1989, prior to use within the WHP in Antarctic waters. Therefore, many calibration points were taken, especially close to and below 0°C. The shape of the calibration curve is striking: although the calibration is almost linear with a small quadratic term over most of the range, i.e. between 0 and 25°C, we observe a strong discontinuity of 2 mK at 0°C when proceeding to lower temperatures. The blow-up in Fig. 1d demonstrates this more clearly. No polynomial regression can properly approximate such a discontinuity.

Two further MKIIIB-CTDs, NB3 (Fig. 1b) and NB2 (Fig. 1c), owned by the Institut für Meereskunde in Kiel, IFMK, were calibrated in the institute's laboratory over the whole oceanic range in August 1990. Resolution of the IFMK calibration at 0°C and less was not required to be as good as in the SIO calibration because the instruments were to be used in the subtropics of the South Atlantic at temperatures well above 0°C. Nevertheless, the discontinuity, or at least strong nonlinearity, of the calibration characteristics close to 0°C for both instruments is similar to that of the S/N 1069 CTD calibrated at SIO.

Additional calibrations of several other MKIIIB temperature sensors (not shown here) were performed at SIO, at IFMK and at the Institute of Oceanographic Sciences in Wormley, U.K. (P. M. Saunders, personal communication, 1993) as well. All confirm the above findings. Both SIO and IFMK use platinum reference thermometers Pt25, but with bridges made by different manufacturers; also, with a different type of CTD which resolved 1 mK in temperature, IFMK could not determine a discontinuity at 0°C. Therefore, we conclude that the observed discontinuity at 0°C is inherent in MKIIIB CTDs, and due neither to the calibration procedures nor to the calibration instruments.

Instead, the first step in the digitization process, namely detecting polarity or the sign, seems to produce the nonlinearity in the temperature measurement. Note that all calibrations mentioned above were performed in laboratory baths with stable temperature (better than 0.5 mK). We therefore do not expect that even slight changes in analog inputs during digitization, which takes only about 0.5 ms for a single measurement compared to the 150 ms time constant of the sensor, account for the observed nonlinearities.

To meet the WHP requirements for precision in temperature, the observed deviations from smooth calibration curves at 0°C must be removed. For the MKIIIBs NB3 and the NB2 (Figs 1b and 1c), where deviations are strongly nonlinear but not really discontinuous, this was achieved by fifth order polynomial regressions with residuals <1 mK over the whole range and more than 10 degrees of freedom in the approximation. Such an approximation would not help in the case of the MKIIIB S/N 1069 with its obvious discontinuity. In this CTD, the temperature range was shifted such that zero voltage now reads outside the oceanic range at -3°C. Note that when this procedure is applied, the 0°C display of the deck unit will correspond to -3°C *in situ* temperature and that the high end reading will be shifted to lower temperatures too. The proposed hardware change is offered as part of an upgrade of the CTD by the manufacturer (now General Oceanics Inc., personal communication, 1994).

Let us add that this shift will not remove additional (probably smaller) discontinuities which may occur where other significant bits change, especially at the half range count 32768, close to 15°C. However, for oceanographic applications, the described discontinuities close to 0°C are much more important to account for than others which may occur at higher temperatures, mostly within the main thermocline with its high oceanic variability.

3. CONDUCTIVITY CORRECTION

Another problem with MKIIIB measurements becomes obvious from the temperature salinity relation shown in Fig. 2. It displays raw data from the deep part of a 1986 station in the northeast Atlantic that have been converted to physical units and subsampled to be monotonic in pressure, only. None other than the internal calibration as delivered by the manufacturer is applied. At potential temperatures of 2.68 and 2.21°C, step-like changes in calculated raw salinity are observed. These jumps in the temperature–salinity relationship both also show up at the raw conductivity value $C = 32.768$ mS cm^{-1} (Fig. 2a; note that C in Fig. 2 has been offset by -30 mS cm^{-1}). Coming from higher values while the CTD is lowered, the critical value is held for a while before the output gets below it. This causes the jump to higher salinities at 34.948. When the CTD is further lowered, a minimum in conductivity is passed. Under higher pressure, conductivity increases and is

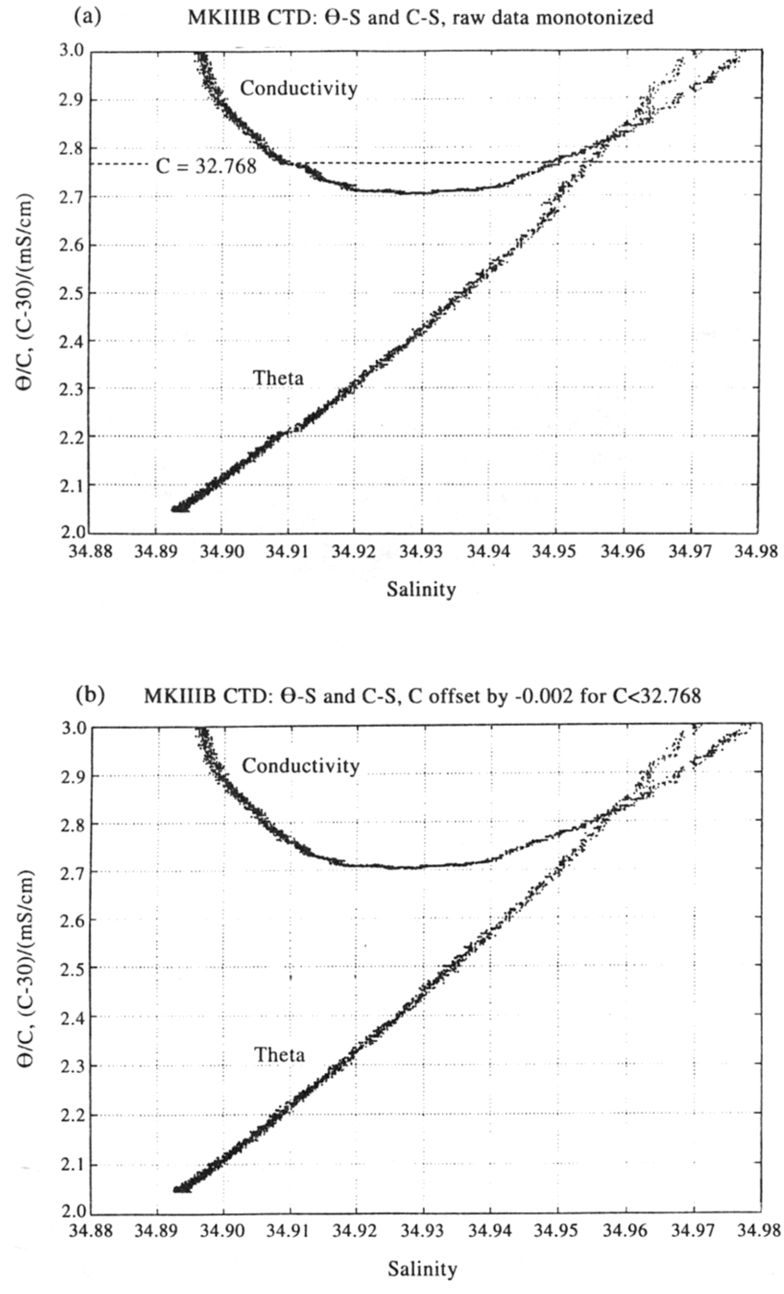

Fig. 2. (a) Steps in the relation of temperature and salinity are caused by a discontinuity in the conductivity sensor's half-range output at 32.768 mS cm^{-1}. Note that conductivity output passes the critical value 32.768 mS cm^{-1} twice while the CTD is on the way down (right to left in the figure). (b) The steps are removed by adding $C3278 = -0.002$ mS cm^{-1} when the sensor output $C \leqslant$ 32.768 mS cm^{-1}.

held again when the critical value is reached at 34.91, and this causes the jump back in salinity to lower values. These jumps are not due to a change in water masses as careful inspection of many MKIIIB-CTD profiles obtained with different CTDs in different ocean areas like the subtropical eastern North and the South Atlantic have shown. Similar steps in salinity occur whenever the uncalibrated conductivity cell output passes the value 2^{15}, i.e. the 32.768 mS cm^{-1} half-range value. Its size may vary with the rate at which conductivity is changing, and therefore may not be a constant and may weakly depend on each CTD and each profile.

To remove the jumps is rather simple. Once the output is equal to or below the critical value of 32.768 mS cm^{-1}, an offset C32768 is added, which has to be determined experimentally for each CTD and each profile. For the CTDs and profiles under investigation, the offset C32768 was between −0.002 and −0.001 mS cm^{-1}, depending on the CTD, but for each CTD it was effectively constant for similar oceanographic conditions and lowering speeds, e.g., during a cruise. If the correction procedure is applied, the jump in salinity is removed almost completely except for small spikes that may remain in some records where $C = 32.768$ mS cm^{-1} is held. These can be removed easily during further processing (Fig. 2b).

4. PRESSURE SENSOR OUTPUT CORRECTIONS

In the MKIIIB-CTD, a stainless steel strain gauge pressure transducer is used to measure pressure. The early models were produced by Standard Controls; later versions are made by Paine Instruments, with no significant differences in their characteristics. The specifications quoted by the manufacturers have been found to be generally conservative, and the sensors have proven to be dependable and of adequate sensitivity. With an understanding of their function, and adequate corrections applied in processing, an accuracy of 2 dbar or better can be obtained under most conditions. The errors associated with the uncorrected pressure signal may not appear to be significant as far as pressure is concerned. However, the impact on calculated parameters should not be forgotten; an uncorrected error of 4 dbar in pressure produces an error in calculated salinity of approximately 0.002.

4.1. *Static and dynamic responses*

There are several characteristics of strain gauge transducers which contribute to measurement errors of significant magnitude in oceanographic applications. We may distinguish between errors which appear more or less as static, and errors which occur as dynamic responses to changing environmental conditions. Within the first category, deviations from linearity of some 2 dbar in pressure response of the transducer can be removed effectively by careful calibration on a dead weight tester. The same holds for deviations of the same order of magnitude due to thermal zero and sensitivity shifts. These can be determined when transducers are calibrated in baths of different temperatures over the oceanic range, although these effects are almost compensated by measuring temperature on a thermistor attached to the outside of the pressure sensor (but see below for dynamic effects). Mechanical hysteresis of the order of 5 dbar may occur when, after a transducer has been brought to high pressure, it is unloaded to lower pressure. Although it

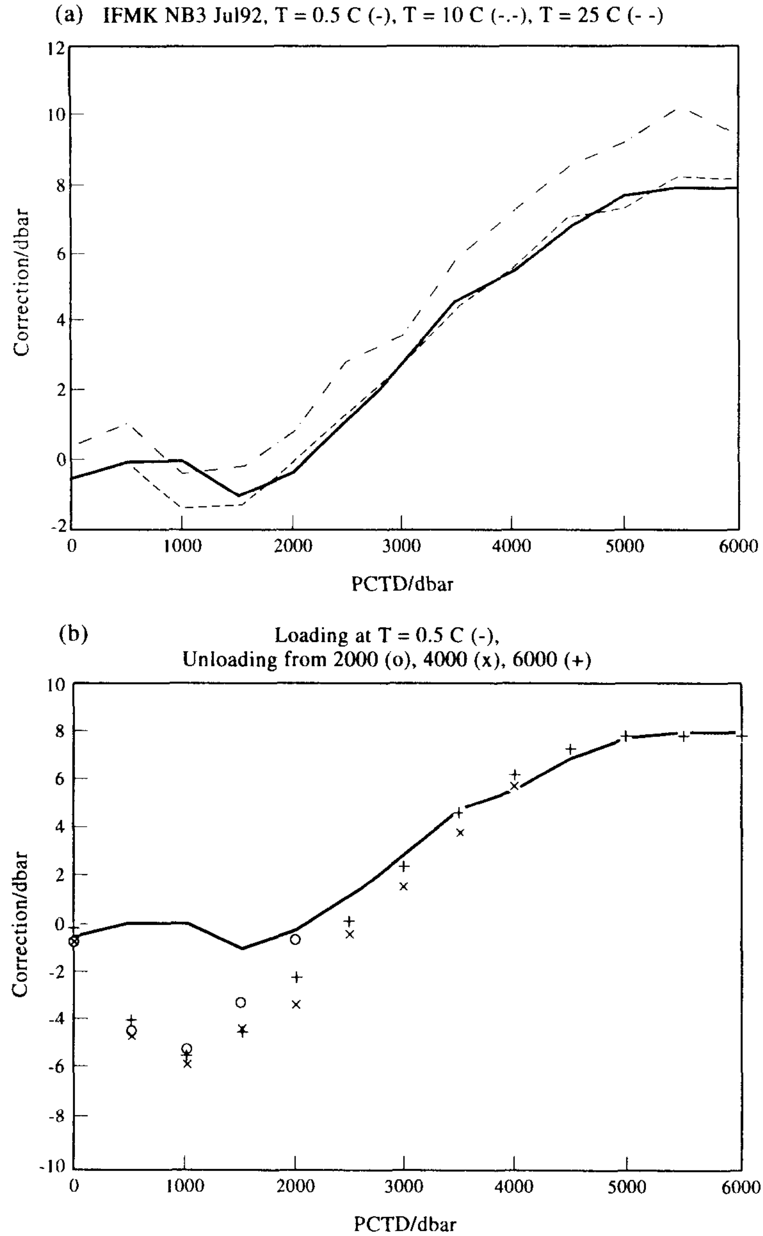

Fig. 3. Static corrections for a MKIIIB pressure sensor: (a) increasing pressure at three different temperatures; (b) mechanical hysteresis for three different maximum loads (O, 2000 dbar; ×, 4000 dbar; +, 6000 dbar) compared to the loading curve (straight line) all at a temperature of 0.5°C.

takes some time for the sensor output to reset to the initial value after being brought back, we consider this type of response also as static and treat it together with the others above.

In Fig. 3 we display the results of a static pressure sensor calibration. Note that only slowly varying environmental temperature, if not thermal equilibrium, is required to perform a static calibration adequately. Corrections to be applied to loading curves depend nonlinearly on pressure readings P_{CTD} and although the shapes of the correction curves do not change much for various constant temperatures (Fig. 3a), a simple polynomial approach obviously cannot model the temperature dependencies. Mechanical hysteresis necessitates up to 5 dbar corrections (Fig. 3b), a quantity which cannot be neglected when conductivity cells are calibrated *in situ* with salinities derived from bottles closed on the way up. Here, too, the response is highly nonlinear and in many cases cannot be easily modeled by polynomials.

While the response to changing pressure may be considered to be instantaneous, the transducer's response to changing temperature is not. As the transducer is threaded into a port drilled through the CTD pressure case endcap, which is located on the inside face of the CTD endcap and surrounded by a substantial thermal mass of stainless steel of relatively low thermal conductivity, the sensing element of the transducer is not in immediate contact with flowing sea water, but is insulated by both the water filling the port and the material in which the sensing element is enclosed. Thus, in a changing temperature field, the pressure sensing element in the transducer may be at a temperature which is 10° or more different from that of the surrounding water, including temperature gradients on the element itself. Continuous but slow adjustment of the sensing element's temperature to the outer temperature changes its pressure output, which is complicated, of course, by nonzero profiling velocity and environmental temperature gradients.

To reduce the response of the sensor under transient changes of temperature, the manufacturer uses a resistive temperature-compensating element in the internal circuitry of the transducer. Ideally, this element would exhibit the same response time and yield a response to temperature changes equal in magnitude but opposite in sign to that of the strain gauge, so that temperature effects would be exactly canceled. In practice, this compensation is not exact, one reason being that the time required for both the strain gauge and the compensating element to reach full temperature equilibrium (or full response to temperature changes) may not be the same. A second one is that the thermistor which is adapted outside the pressure sensor for static compensation has much larger time constants (up to 1–2 h) than the pressure sensing element because of its thermal insulation. This time constant may mismatch that of the compensation circuit.

The final response, with all compensations mentioned above applied, can be demonstrated by plunging a CTD's pressure sensor from a stirred warm water bath into a stirred cold water bath and back again (dunk test; Fig. 4a). Typically, for many MKIIIB-CTDs, a roughly 20 K temperature step causes a pressure sensor output response amplitude of about 4 dbar and a half-response time of order 1800 s. The effect of all compensations is adequate to bring the overall transducer response to within the established specifications of the manufacturer. Nevertheless, in order to achieve the high accuracy required for the WHP, further corrections are needed.

One concept to start dynamic correction with is to avoid the possible mismatch of time constants from the compensation circuit and the outer thermistor. Consequently, one would disconnect the thermistor static temperature compensation and thus treat the pure pressure sensor response only. Such a procedure will lead to larger response amplitudes and shorter response times, avoid mismatches in time constants, and result in well-behaved pressure sensor response curves. This concept is favored by the two contributing authors from the SIO. In many MKIIIBs, however, analog compensation as provided by the manufacturer still makes sense, since a smooth response curve of small amplitude

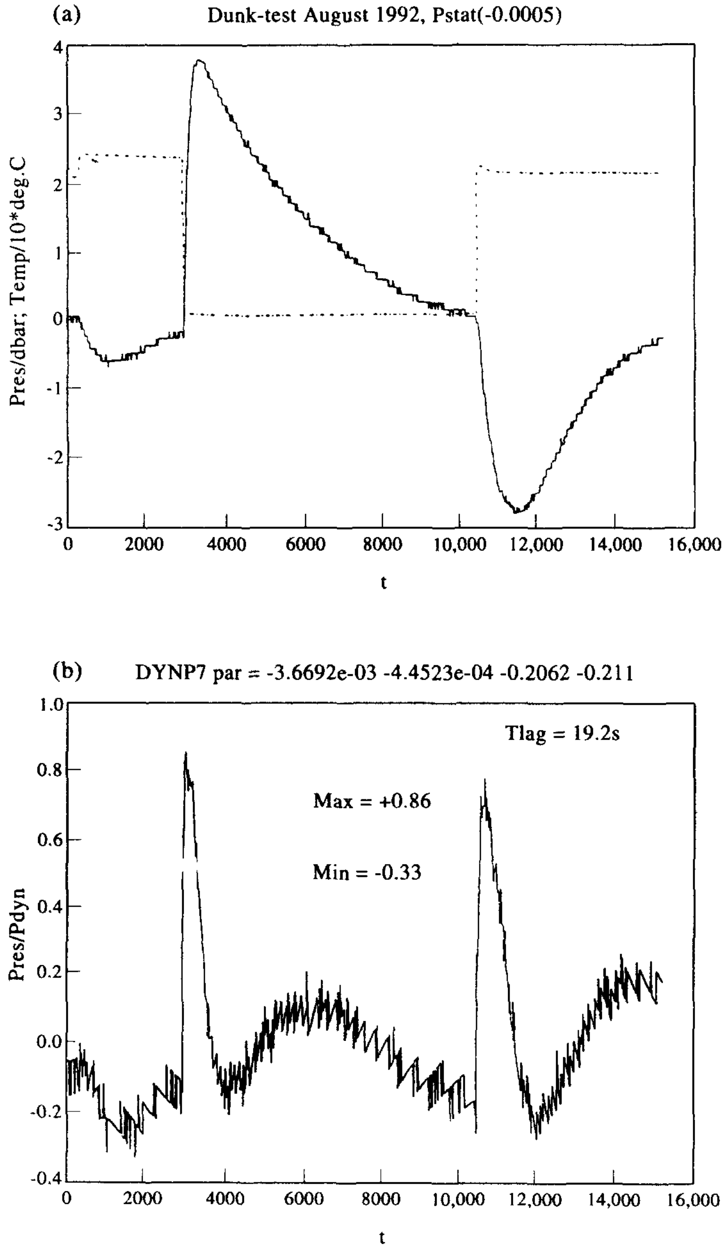

Fig. 4. (a) Dynamic response of a MKIIIB compensated stainless steel strain gauge sensor (thick line) to temperature steps (broken line). Units are time t(s), pressure response Pres (dbar) and temperature Temp (per 10°C). The CTD's sensor was deployed from air pressure to a stirred warm water bath, then to cold and back to warm water again, *in situ* pressure in baths being 0.2 dbar. (b) Residual of dynamic correction for the response using the model and parameters of equations (6) and (7).

results (e.g., Fig. 3). Therefore, at IFMK, the analog compensation is kept in such cases. In both concepts the correction schemes which may be applied do not differ in principle from each other. We, therefore, without losing generality, may restrict the discussion of such schemes to sensors where the hardware has not been altered before.

From the above discussion an adequate correction scheme must include both static corrections for nonlinearity, thermal shifts and mechanical hysteresis, and a dynamic correction when temperature varies with time. Since thermal equilibrium is assumed for static corrections, a dynamic correction P_{dc} to the sensor's output P_{CTD} should be applied to prior to the static correction to achieve an estimate of the static response at the actual outer temperature. The static correction P_{sc} applied to this estimate of the static response then gives the best estimate P of *in situ* pressure. However, since all corrections are small compared to the range, we may assume that they can be superposed linearly, and we may write:

$$P = \mathrm{POL}(P_{CTD}, T_0) + P_{sc} + P_{dc}. \tag{2}$$

Here, $\mathrm{POL}(P_{CTD}, T_0)$ is the basic polynomial calibration of the pressure sensor's output P_{CTD} over the full range in loading mode at a fixed, preferably low, temperature T_0. In cases where such a polynomial approach is not appropriate due to strong nonlinearity, $\mathrm{POL}(P_{CTD}, T_0)$ must be replaced by the output P_{CTD} itself, and the basic calibration is incorporated into the static correction P_{sc}. Finally, P_{dc} represents the dynamic correction, and P is the corrected best estimate of *in situ* pressure.

4.2. *Static correction*

P_{sc} can generally be estimated by interpolation from a table of calibration data. It may be organized such that the first column contains the reference pressure, followed by columns with the first loading curve as measured at the lowest temperature, followed by unloading curves at that same temperature with increasing maximum load, then continuing with loading and unloading curves for the next higher temperature until the warmest loading and unloading curves. Alternatively, the table may refer all calibration data to an already performed basic calibration which is valid for one loading curve, preferably one at low temperatures.

Since, under transient temperature changes, the pressure sensor does not feel the surrounding temperature as measured by the CTD's temperature sensor, a 'lagged' temperature representing that on the sensing part of the pressure sensor should be taken for interpolation. It can be calculated recursively from the CTD's measured temperature and without making a substantial error be the same as that used for the dynamic correction discussed further below.

The interpolation of P_{sc} is initialized when *in situ* conductivity exceeds a previously established 'in-water' value. The corrected pressure is interpolated in two dimensions from those four calibration points which were measured in loading mode at temperatures less than and higher than the current lagged temperature and which values bracket the sensor's output. A final offset, i.e. that correction which is required to bring the corrected pressure to 0 dbar at the profile's start at the surface, is added throughout the cast. It represents the pressure sensor's zero drift.

When pressure reverses on the way up, the interpolation of P_{sc} enters the unloading

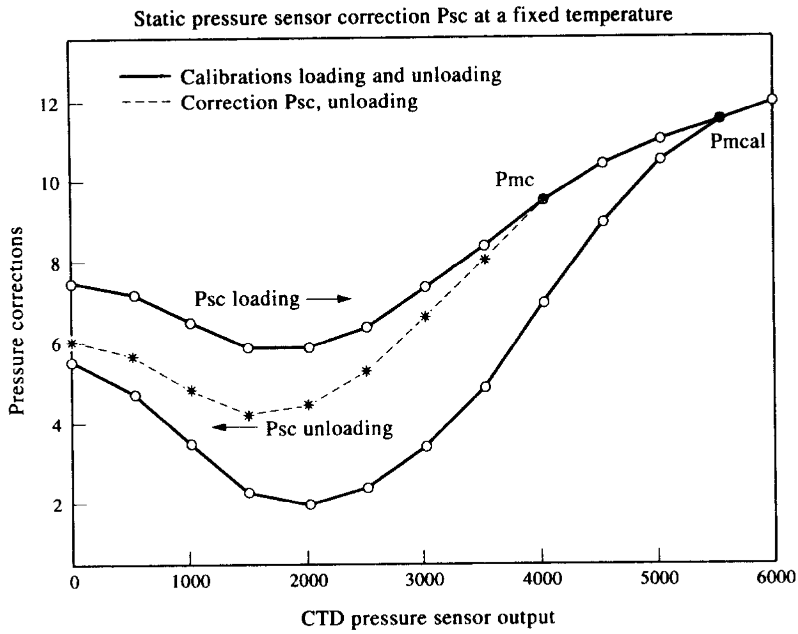

Fig. 5. Scheme for static correction P_{sc} of pressure sensor output at fixed temperature. Solid lines represent calibration curves in loading (upper curve) and unloading (lower curve) mode. Starting at the surface, P_{sc} is interpolated on the loading curve until it reaches the maximum cast pressure at P_{mc} where it changes into unloading mode due to hysteresis. Here P_{sc} is interpolated from the loading P_l and unloading P_u curves and weighted: $P_{sc} = P_l + (P_l - P_u)^*(P_{CTD} - P_{mc})/P_{mcal}$.

mode (Fig. 5), again at temperatures that bracket the current lagged temperature. To account for mechanical hysteresis, in addition to the loading curves, those unloading curves are selected that have the least maximum pressure higher than the maximum cast pressure. For both temperatures, static corrections are interpolated from the chosen loading and unloading curves and weighted with the differences between maximum cast pressure and pressure reading divided by the maximum calibration pressure. The final correction is found from interpolation between these values using the current lagged temperature. If the CTD is again lowered before hysteresis has been reset, interpolation follows the unloading scheme until the previous maximum cast pressure is reached. From then on, the mode reverses to loading again.

If a lagged temperature is encountered which is outside the range of calibration, or if the CTD's pressure reading slightly exceeds the maximum calibration values, an extrapolation with constants is performed. This may incur some risk with certain types of sensors of nonlinear temperature response, but it is not generally a problem with the MKIIIB pressure transducers.

4.3. *Dynamic correction*

Recently, two models have been published which suggest methods to correct for the dynamic effects of pressure sensors to temperature steps. Chiswell (1991) uses linear system theory to determine the dynamic correction of a Paroscientific Digiquartz sensor-implemented in a SeaBird 911-CTD as:

$$P_{dc} = -h^*T = P - P_s. \tag{3}$$

Here, $P_s = \mathrm{POL}(P_{CTD}, T_0) + P_{sc}$ denotes the statically corrected pressure, P is the best estimate of *in situ* pressure, T is the outer temperature as measured by the CTD, h is the transfer function describing the heat transfer from the surrounding water to the pressure sensor, and * denotes convolution. The transfer function h can be determined experimentally from a plunge test as the time rate of change of the pressure response P_s divided by the amplitude of the temperature step (provided the static calibration is properly done and certain constraints on h are observed). Application to dunk tests yielded response amplitudes of 5 dbar on 18 K steps and residuals of up to 1 dbar.

Chiswell's method, of course, is also applicable to MKIIIB strain gauge sensors. As noted in the paper, however, use of the convolution integral in equation (3) requires knowledge of a long 'history' of temperature ahead of a cast, and little is known about the stability of the transfer function h. Also, even small errors in h, e.g., from nonlinear parts of the response, may lead to large errors in P_{dc} by the convolution involved.

In an attempt to replace the stainless steel strain gauge of a MKIIIB-CTD by titanium strain gauge sensor, also marketed by Paine Instruments, Millard *et al.* (1993) invested the response characteristics of this sensor. While linearity and hysteresis of the new sensor prove far better compared to the stainless steel sensor, the noise level is higher by a factor of two. Not applying any internal temperature compensation, the dynamic temperature response can be reduced to the order of a MKIIIB stainless steel sensor only if thermal insulation is performed extremely carefully as described in the paper and offered as upgrade by the supporting company (now General Oceanics Inc., personal communication, 1994). Shape and amplitude of the resulting dynamic response are then similar to that of a MKIIIB with stainless steel sensor and internal compensation, and thus correction methods developed for the upgraded MKIIIB may also hold for the original instrument. Using the internal temperature T_p as measured at the pressure sensing element and the water temperature T as measured by the CTD's main temperature sensor, the authors suggest a dynamic correction based on the time rate of changes in both temperatures and their difference:

$$P_{dc} = c(\mathrm{d}T/\mathrm{d}t) + b(\mathrm{d}T_p/\mathrm{d}t)\,\mathrm{abs}\,(T_p - T). \tag{4}$$

A plunge test with a 20 K step resulted in a roughly 3 dbar amplitude response and order 0.5 dbar residuals after correction. Note that when this method is applied to a MKIIIB with stainless steel strain gauge sensor, the temperature T_p is not measured but must be modeled recursively as lagged temperature from T.

We have performed several alternative models to determine the dynamic correction P_{dc} for the dunk test shown in Fig. 3. In all models, we have used two recursively lagged temperatures representing 'outer' and 'inner' temperatures of the sensor. The best results were obtained with the simple model:

$$P_{dc} = aT_o - bT_i, \tag{5}$$

where T_o and T_i are modeled outer and inner temperatures at the pressure sensor, respectively, and are calculated recursively at 0.5 s intervals as lagged water temperature:

$$\begin{aligned} T_o(i) &= T(i) - (T(i) - T_o(i))\exp(r_o(t(i) - t(i-1))) \\ T_i(i) &= T_o(i) - (T_o(i) - T_i(i))\exp(r_i(t(i) - t(i-1))). \end{aligned} \tag{6}$$

The four coefficients a, b, r_o and r_i were determined using nonlinear least square methods:

$$\begin{array}{ll} r_o = -4.04 \times 10^{-3}\,\mathrm{s}^{-1} & r_i = -4.14 \times 10^{-4}\,\mathrm{s}^{-1} \\ a = -0.19\ \mathrm{dbar\,K}^{-1} & b = 0.21\ \mathrm{dbar\,K}^{-1} \end{array} \qquad (7)$$

The residual of the dynamic correction with maximum amplitude of 0.8 dbar is shown in Fig. 4b. The coefficients a and b are close together and, indeed, a three parameter model with $a = b$ gives almost as good results.

The three models may be compared in terms of residuals normalized by the associated temperature step. The values are up to 0.1 dbar K^{-1} for the linear response model (Chiswell, 1991; his Fig. 4c), 0.03 dbar K^{-1} for the model of Millard *et al.* (1993; their Fig. 6b) which uses internally measured temperatures and 0.04 dbar K^{-1} for the lagged temperature difference model [equation (7)]. The relatively high residual of the linear response model may reflect inadequately modeled nonlinear responses as well as lack of knowledge of temperature history.

5. CONCLUSIONS

Several deviations from smooth calibrations of MKIIIB-CTD sensors have been discussed. Those of the temperature and conductivity sensors, despite careful adjustment of the electronics, obviously are associated with the change of significant bits in the digitization process: the sign (temperature) and half-range (conductivity). Although we would expect further discontinuities also for the pressure sensor half-range output and at the next higher bits change of all three sensors, such discontinuities have not been observed so far. The reason is that detecting a discontinuity at the pressure sensor half-range output would require an almost continuous sensor calibration around that point, a task which is not realistic with available dead weight testers. Higher bit discontinuities at all three sensors would have even smaller amplitudes than those shown in the previous sections and thus would be even harder to detect and would not be relevant for presently required accuracies in oceanography.

The temperature sensor's strong nonlinearity, in some instruments even discontinuity of several mK close to 0°C, is most severe. It needs to be removed, especially for measurements in cold waters to meet WHP requirements. Shifting the zero voltage output to −3°C output is strongly recommended for these instruments. We suspect that in many earlier campaigns in which MKIIINs were used, the instrument's calibration was simply based on positive temperatures and linearly extended to negative temperatures. In such cases, temperatures below 0°C may be reported and archived at values too high by 5 mK and more.

Errors of order 0.002 mS cm^{-1} occurring at conductivity cell outputs $\leq$32.768 mS cm^{-1} can be removed by software.

For the stainless steel strain gauge sensor, both a static and a dynamic correction of order 5 dbar must be applied. It is not clear which of the dynamic models discussed here proves best for individual sensors. At present, final maximal errors after dynamic corrections of 0.5–1 dbar at a 20 K temperature step remain in each model. This would fulfill the WHP standards. Ongoing investigations may improve these results.

Finally, we conclude that by implementing the corrections discussed, the standard MKIIIB-CTD can achieve the accuracies required by current campaigns like the World Ocean Circulation Experiment WOCE.

Acknowledgements—We thank two anonymous reviewers for constructive comments. This study was completed while TJM enjoyed the hospitality of Texas A&M University, College Station, Texas, U.S.A. J.H. and T.J.M. were supported by grant 03F0050D of the Bundesminister für Forchung und Technologie, Bonn, Germany.

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